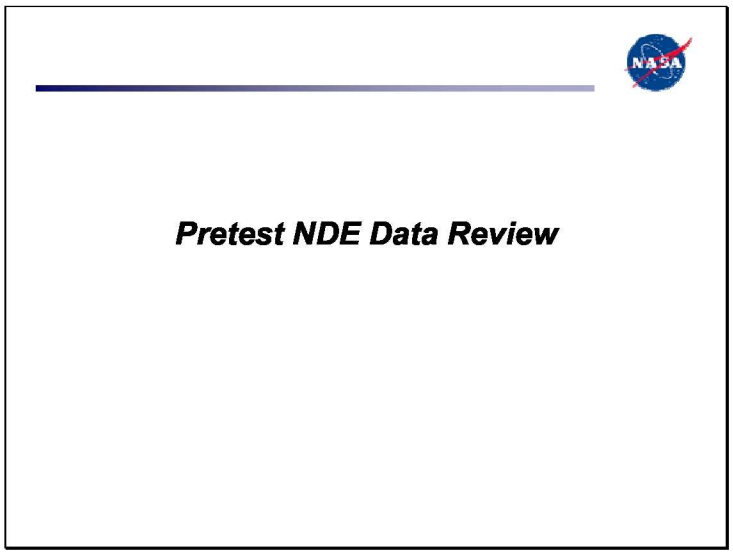
Slide 1

Slide 2

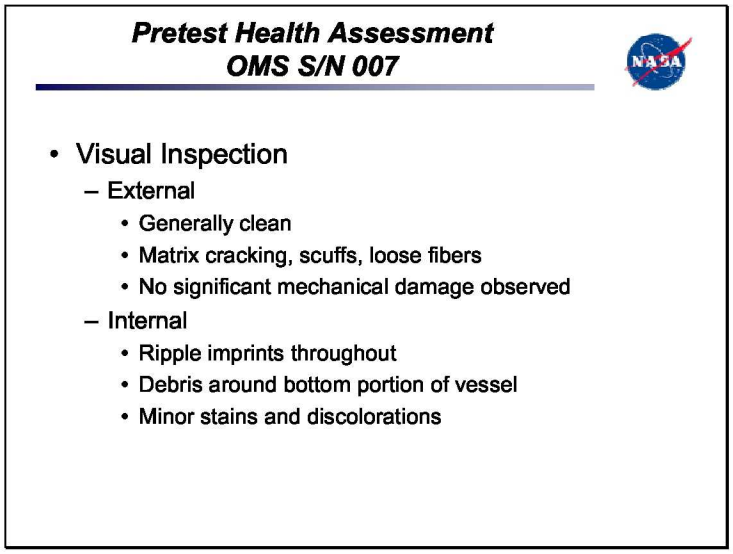
Overview

- Pretest Nondestructive Evaluation (NDE)
  - External/Internal Visual Inspection
  - Raman Spectroscopy
  - Laser Shearography
  - Laser Profilometry
- Real-Time NDE
  - Eddy Current
  - Acoustic Emission (AE)
  - Real-time Portable Raman Spectroscopy
- AE Application to Carbon/Epoxy (C/Ep) COPVs

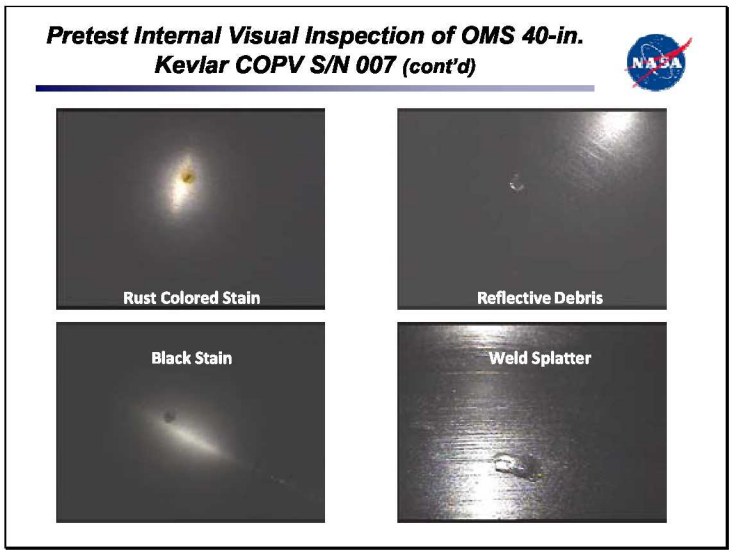
Slide 3



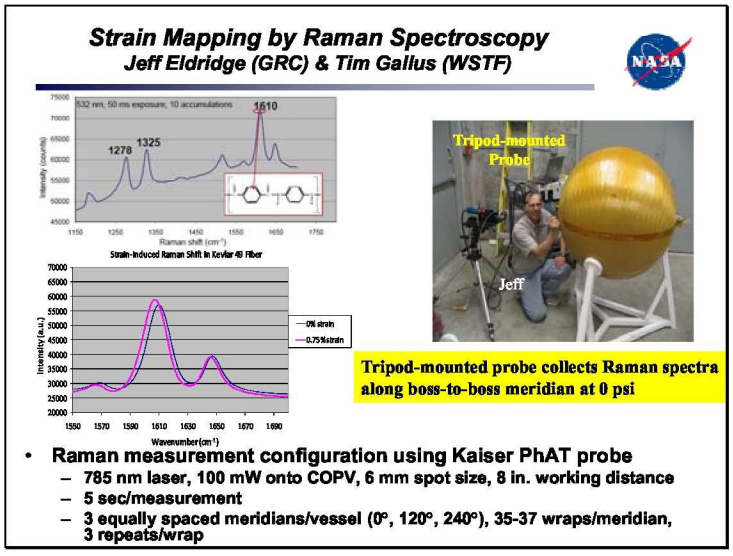
Slide 4



Slide 5

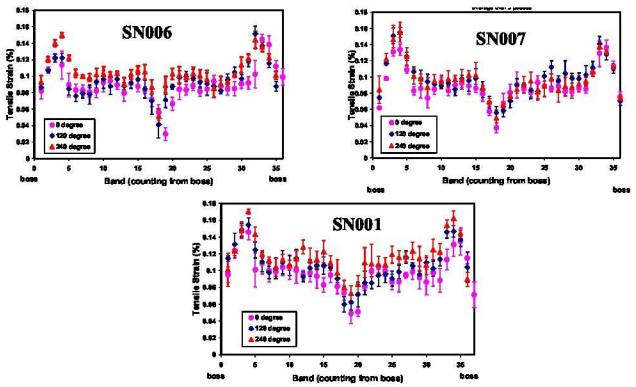


Slide 6



Slide 7

Comparison of Strain Profiles on 3 Orbiter Vessels at 0 psi (0°, 120°, & 240° Meridians)

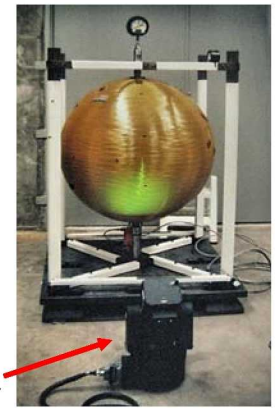


The Orbiter vessel SN007 strain profile was similar to previously tested vessels SN001 & SN006.

Slide 8

Shearography Setup

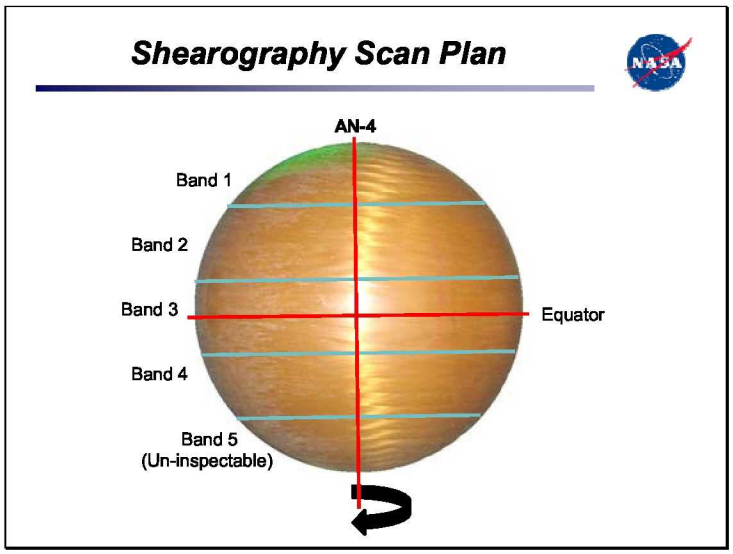
- LTI-5100HD Shearography Camera
- COPV Pressurized with GN_2
- Test Parameters:
  - COPV biased pressure: 70 psi
  - Test pressure differential: 10 psi
  - Shear vector: 0.375 in. x, y
  - Field of view: 14.25 in.



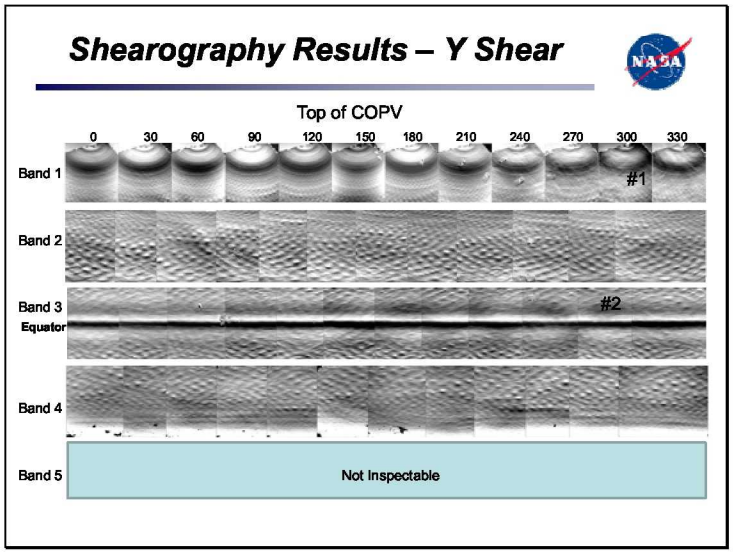
LTI5100 HD on floor for Band 4 Test

Laser Technology Inc.

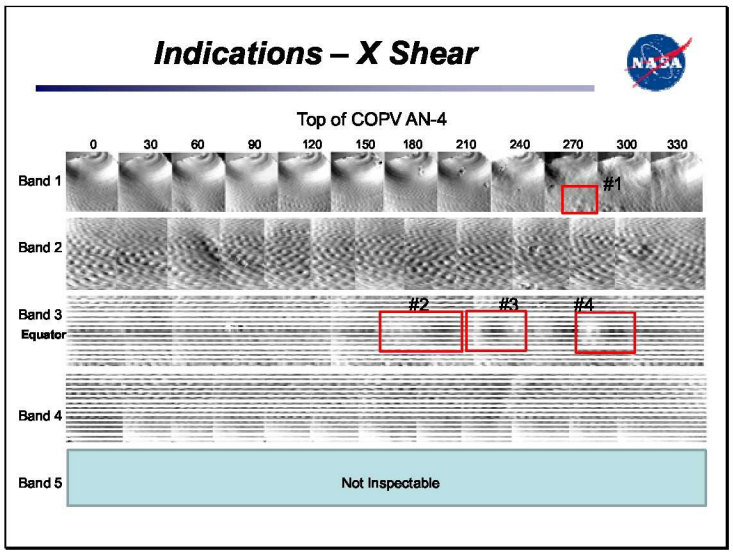
Slide 9



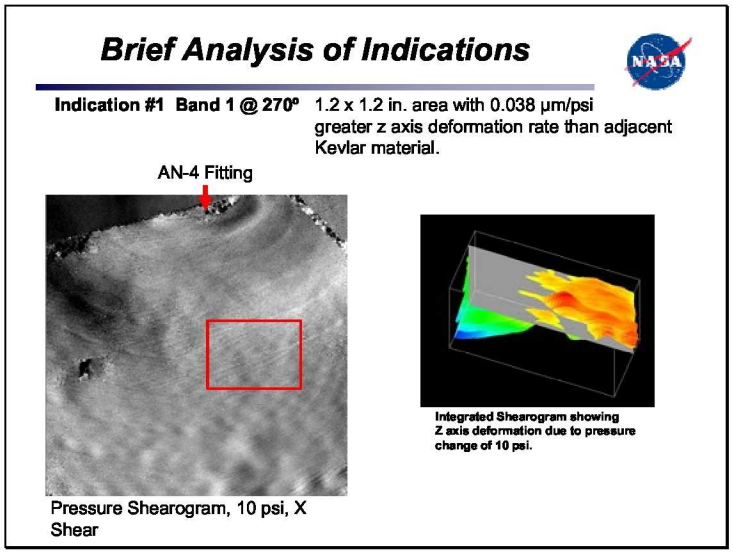
Slide 10



Slide 11



Slide 12



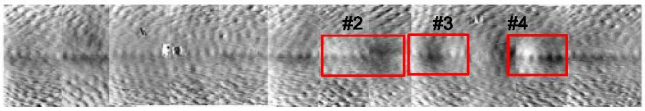
Slide 13

Brief Analysis of Indications

Indications #2, #3, #4

Location: Band 3 @ 170° to 300°, 14 in. below AN-4 fitting, along the center of the equatorial circumferential Kevlar wrap
Size: #2 is 12 in. long, #3 is 9.5 in. long, and #4 is 9.0 in. long

Indications are variations in the Z axis displacement. The circumferential wrap should ideally provide uniformity around the equator. Shearography is detecting slight variations in the strength of this wrap.



Slide 14

Kevlar NDE Reference Standard Helped Quantify Defects

- Manufactured "damage" built into standard
- Wound at OEM
- 18 in. diameter sphere
  - Kevlar-49 fiber thick-walled (24 layers—48 plys)
- Numerous types of damage inflicted during winding process
  - Cut fibers
  - Simulated delaminations

Slide 15

Type of Defects in Kevlar NDE Standard

- Fiber Cuts: 1 in. and 3 in. long cuts (1 and 2 layers deep = 2-4 plys)
- Individual Delaminations: Four sizes of heat-sealed 5 mil FEP Teflon® (1 x 1 in., 1 x 2 in., 1 x 3 in., and 1 x 4 in.)
- Locations kept confidential

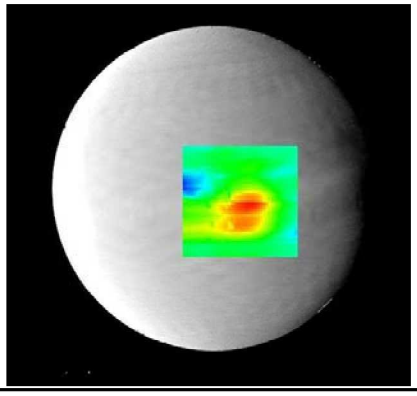
Typical Large Cut

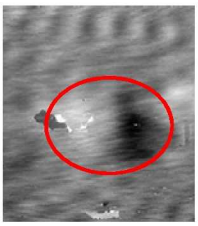

Typical Delamination

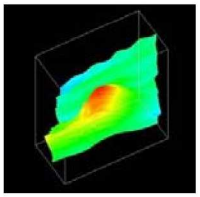
Slide 16

Examples of Shearography Response to Kevlar NDE Standard

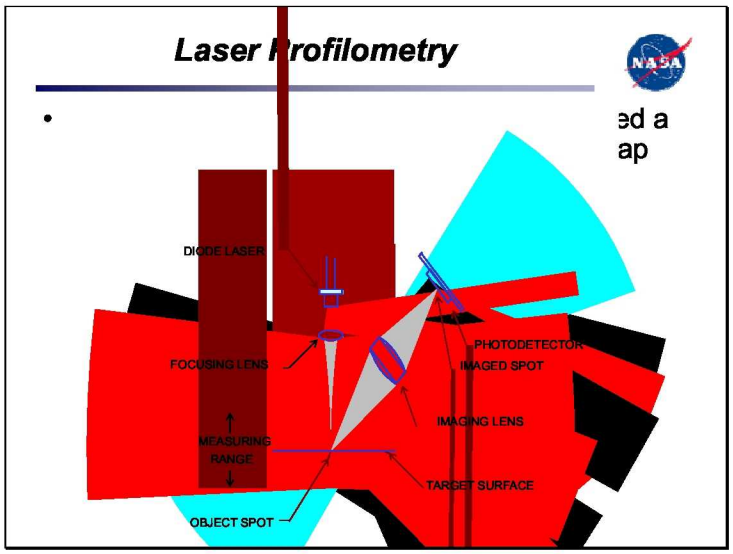
Z axis deformation at this anomaly is greater than adjacent areas of Kevlar wrap by 0.095 µm/psi.



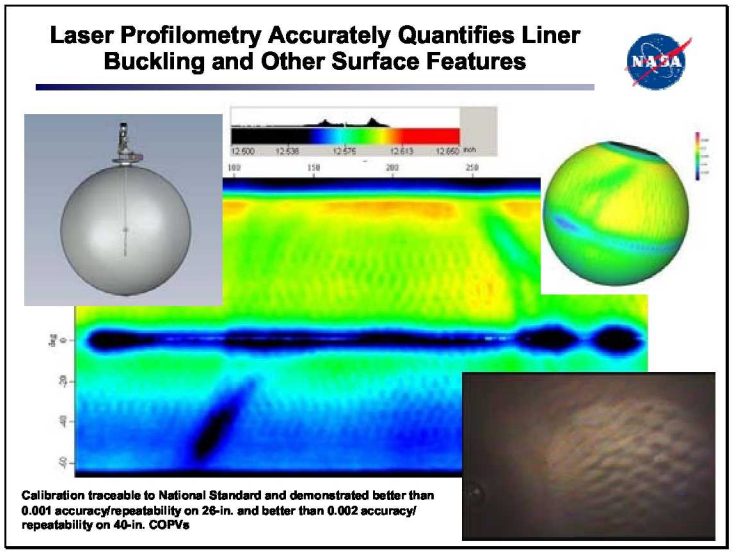




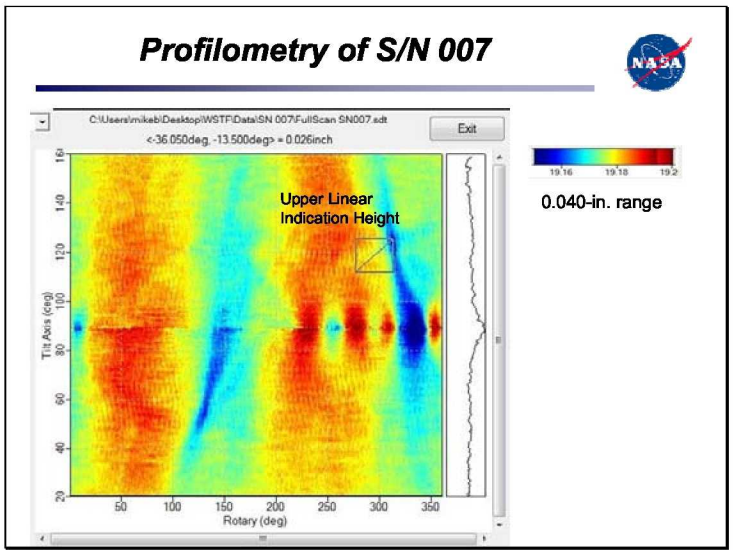
Slide 17



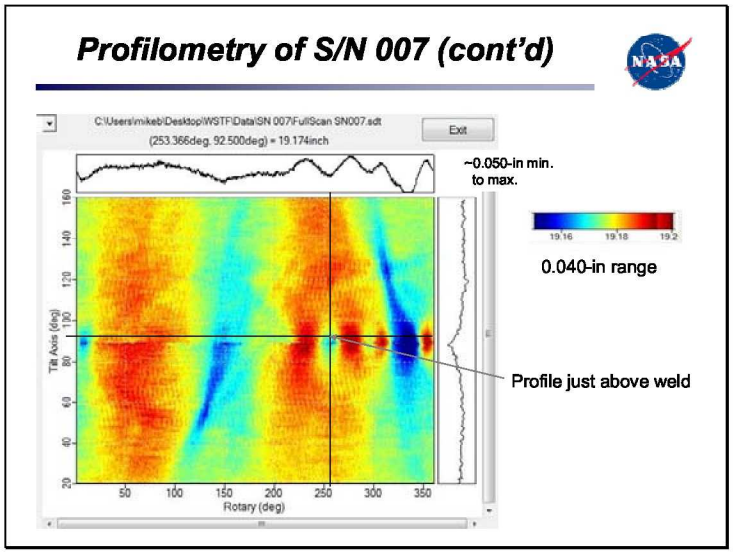
Slide 18



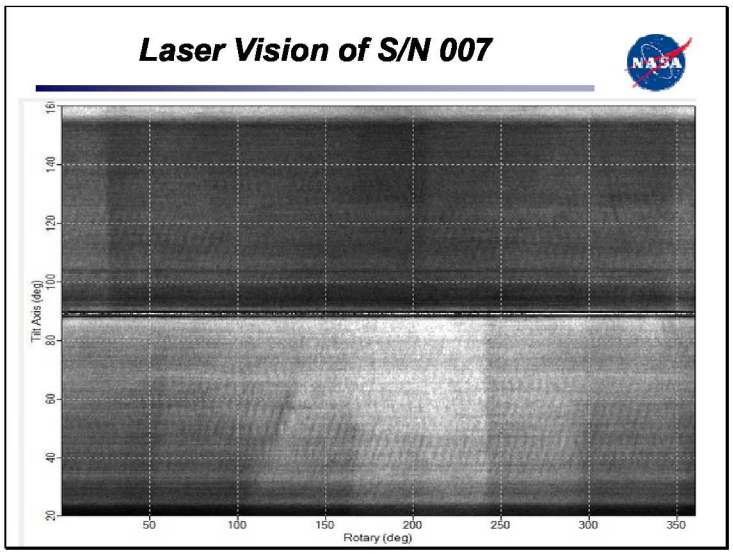
Slide 19



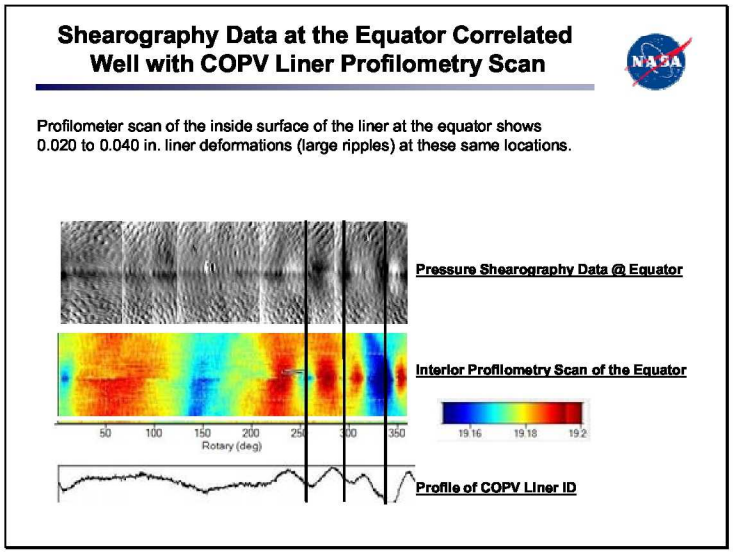
Slide 20



Slide 21



Slide 22



Slide 23

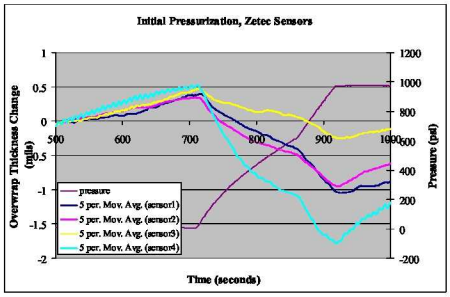
OMS Kevlar Pretest NDE Conclusion

- With exception of the large ripples around the girth well, no indications were observed that were an issue with planned stress rupture testing
- Eddy current (EC) sensors were placed over the peak of each girth ripple and monitored during pressurization to verify the liner did not flex causing a metallic fatigue concern
  - Decrease of stand-off between the fixed composite surface and liner ripple would indicate a liner buckle and associated air pocket
  - Stand-off remained fixed during pressure cycles, signifying that the indications were not a concern

Slide 24

Eddy Current Testing to Address Buckling Question

- Three EC sensors (#1 - 3) were placed over the peak of the largest liner ripple indications, and one sensor (#4) was placed in the liner membrane region as a reference.
  - Response of Sensors #1 - 3 was in family with the membrane reference sensor, indicating ripples were not behaving as unstable "buckles" during pressurization
  - Stand-off change of 1 to 2 mils per 1000 psi was consistent with EC data obtained from other 40 in. Kevlar COPV testing



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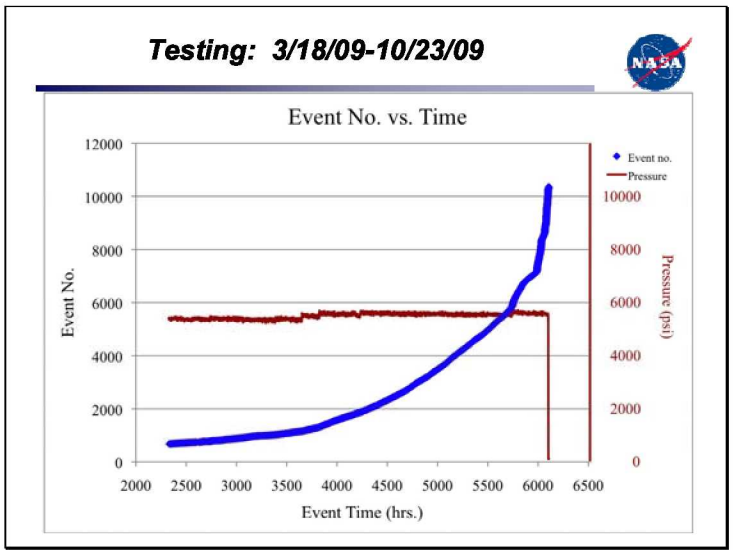
Real-Time NDE

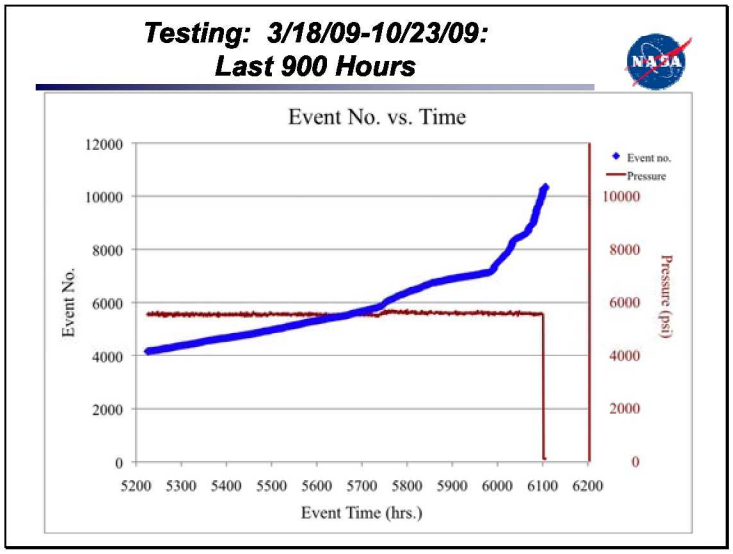
Slide 26

AE Data Review

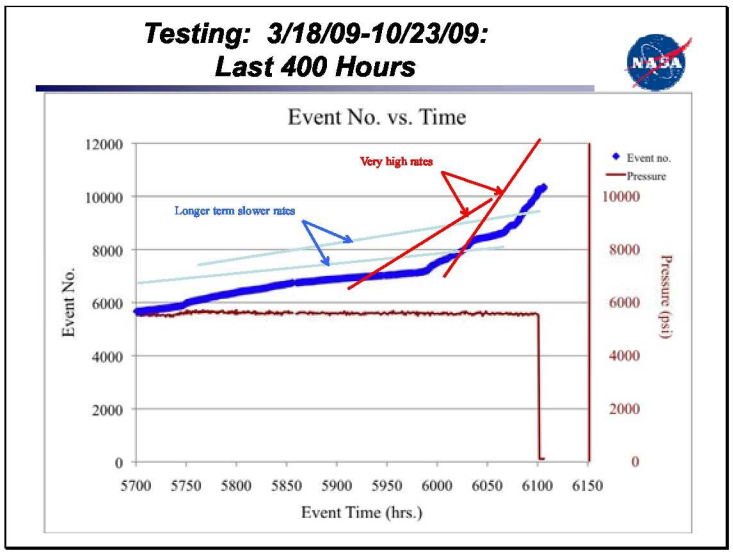
Slide 27



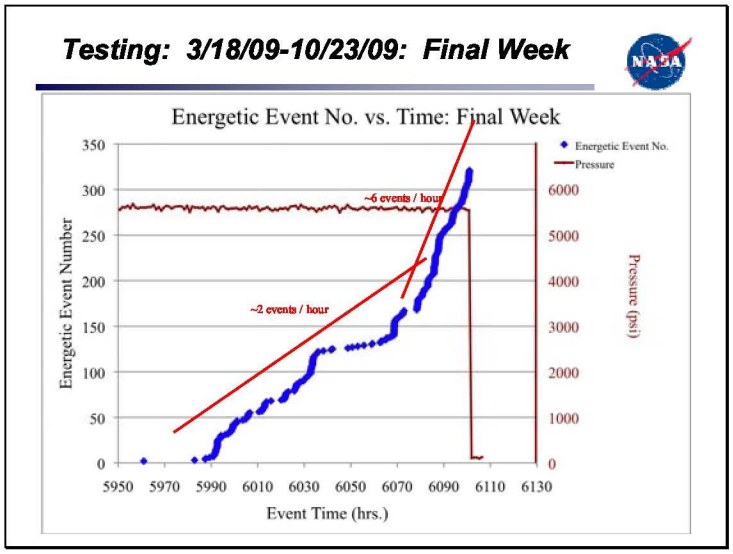
Slide 28



Slide 29



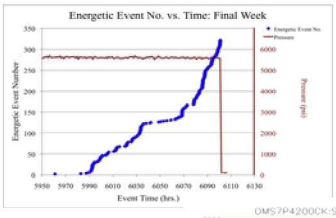
Slide 30

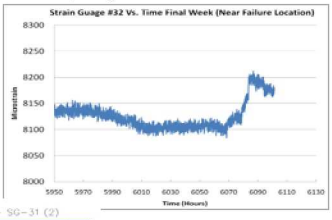


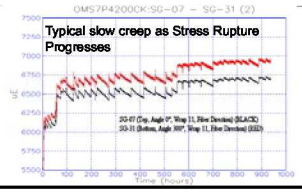
Slide 31

Comparison of AE Events to Strain During Final Week

- AE event numbers show an increase at ~6070 hours
- Strain near failure location increases rapidly near the end

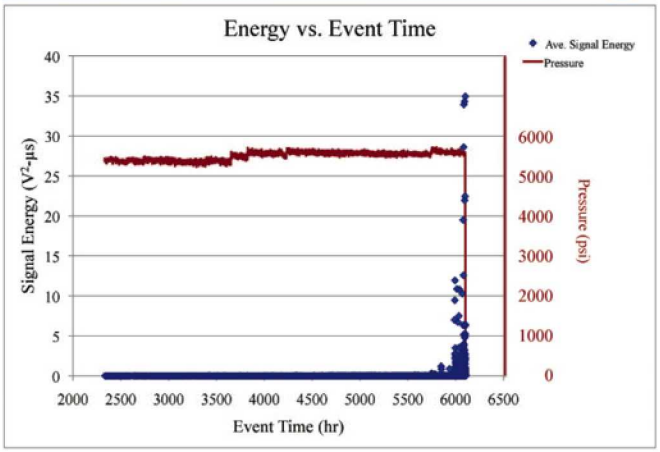




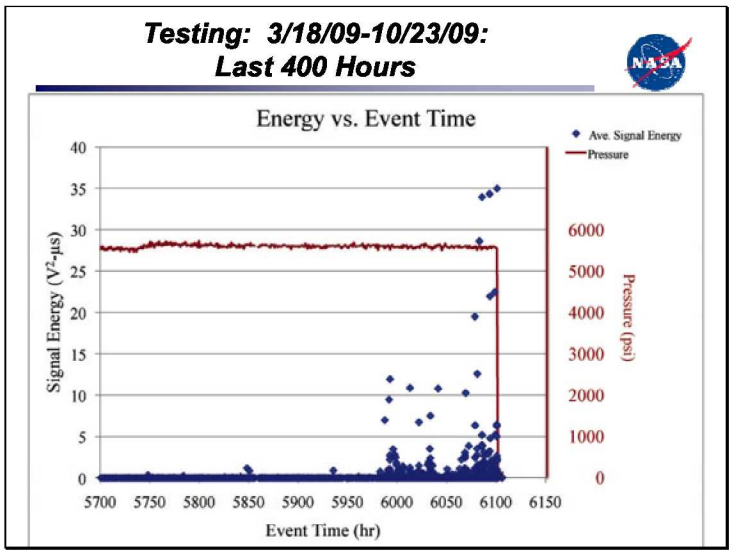


Slide 32

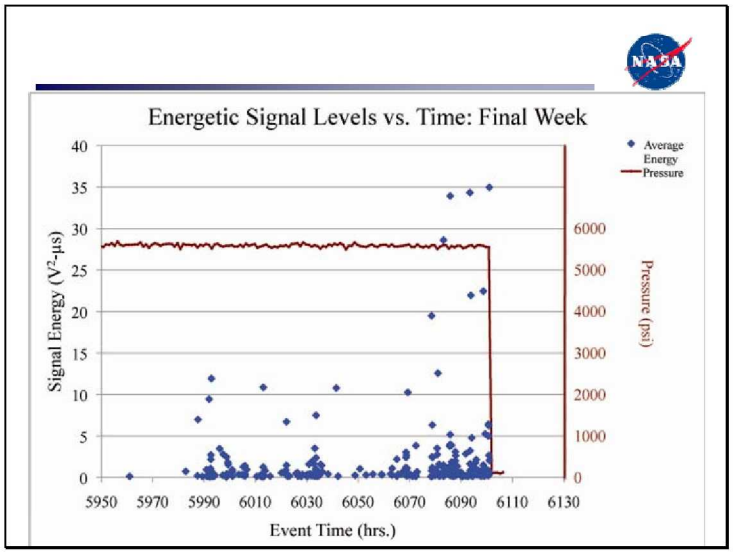
Testing: 3/18/09-10/23/09



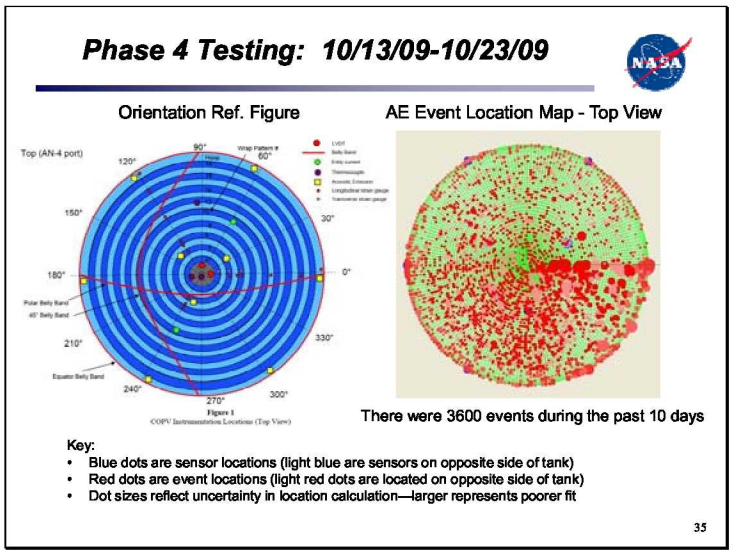
Slide 33



Slide 34

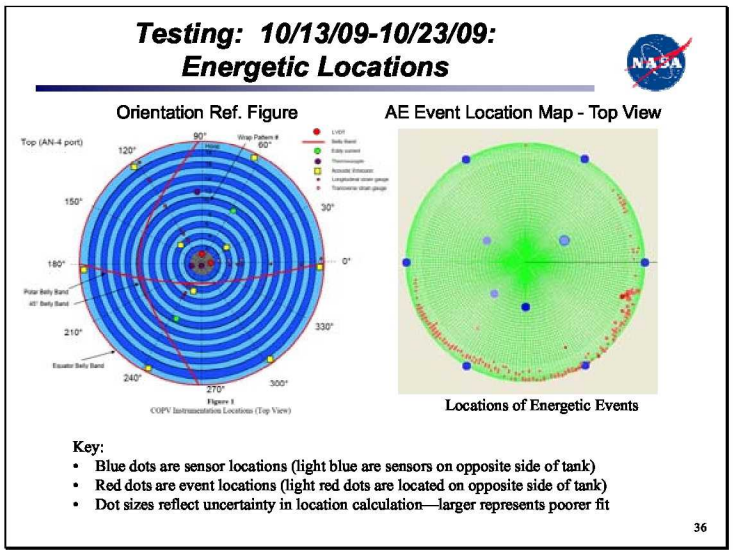


Slide 35



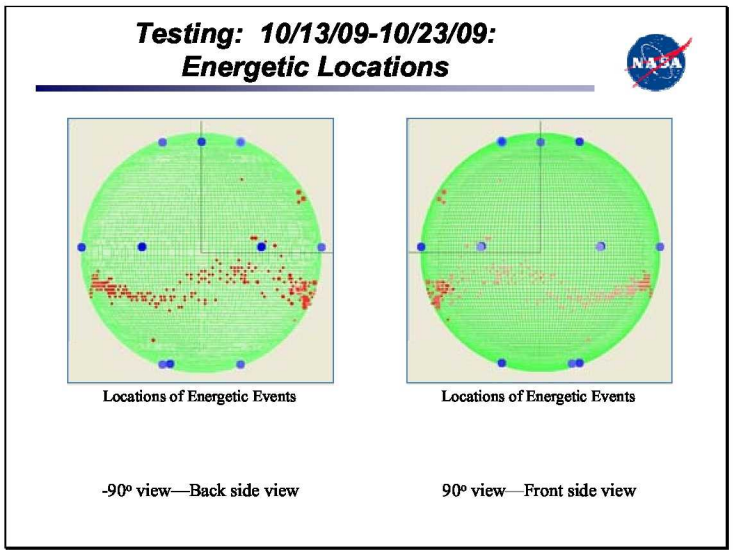
This is a view of all the AE events to date as seen from a top down view. Some event clusters appear near the equator. A few loose groupings near the poles

Slide 36

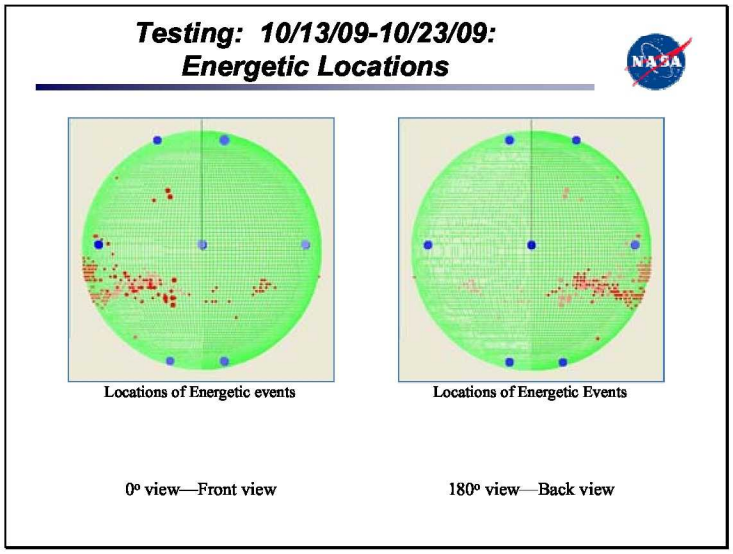


This is a view of all the AE events to date as seen from a top down view. Some event clusters appear near the equator. A few loose groupings near the poles

Slide 37

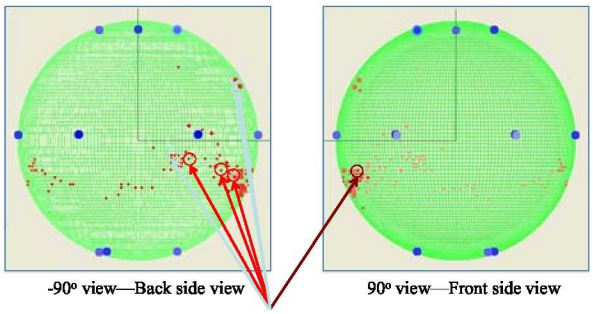


Slide 38



Slide 39

Testing: 10/13/09-10/23/09: Final High Energy Burst (Final 24 h)



-90° view—Back side view

90° view—Front side view

Locations of Energetic Events
Red lines mark the locations of the larger events
The dark red line marks the location at depressurization
(which was the largest.)

Slide 40

AE Summary

- There were two AE event rate increase periods that occurred during the last 7 days. The last rate increase ended in failure.
  - Over 3000 recorded events during the last 10 days
  - More than 300 very energetic events recorded during the last week
  - The rate increases were coincidental with trains of very large energy signal events.
  - The first rate increase for large energy signal events (24 to 96 hours before the end) was approximately 2/hour.
  - The second and final rate increase for large energy signal events (last 24 hours) was approximately 6/hour.
- Event energies rose to very elevated levels during the last 96 hours.
  - High energy events were > 25 times greater than energetic events in the past.
  - The loudest events occurred at the end (last 24 hours).
  - The final event, which was the loudest, was located ~45° below the equator and near the azimuth angle of 45°.

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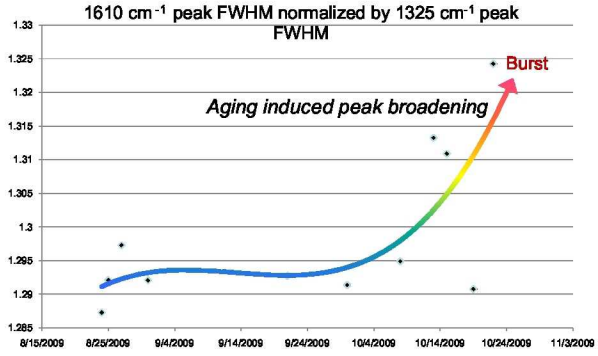
Portable Raman System Developed to Allow Real-time Raman Spectroscopy During Testing

Tim Gallus performing bench top testing of a Raman spectography system prior to installation in the test cell

Slide 42

Real-time Raman During COPV SN007 Stress Rupture Testing - 8/15/09-10/22/09

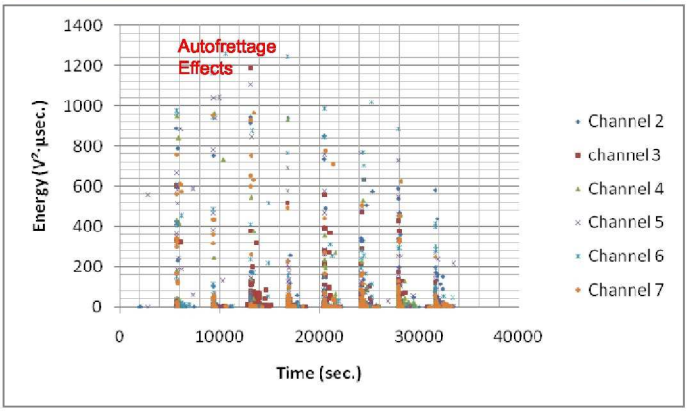


Slide 43

AE Application to Carbon COPVs
Looking to the Future

Slide 44

IM7 C/Ep COPV AE ENERGY EVENTS vs. TIME



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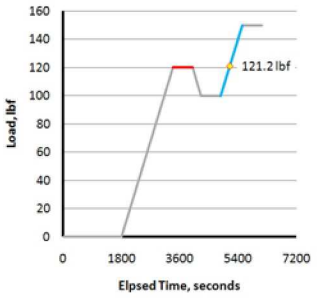
Felicity Ratio

Felicity ratio (FR) given by:

$$FR = \frac{\textit{stress at onset of significant acoustic emission during loading}}{\textit{maximum previous stress plateau}}$$

Example using an intermittent load hold (ILH) profile:



$$FR = \frac{121.2}{120} = 1.01$$

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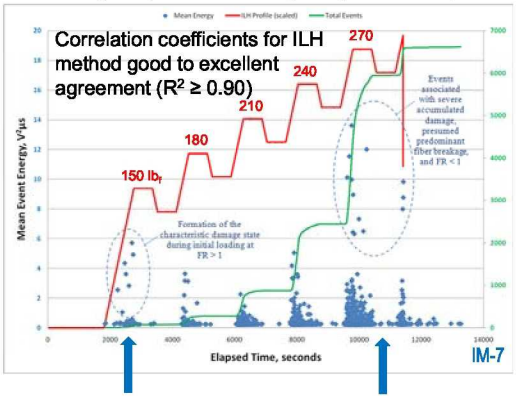
C/Ep Results & Discussion

Regions of high AE activity correspond to events occurring early in COPV life cycle up to catastrophic failure



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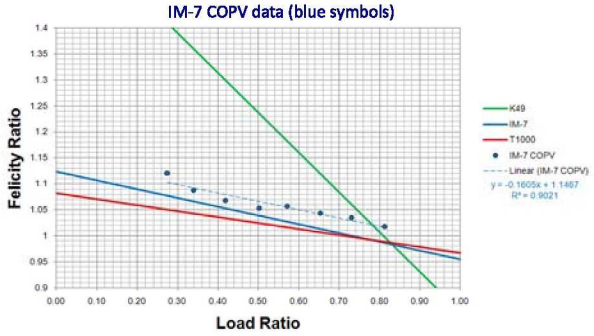
Correlation of IM7 C/Ep COPV AE Felicity Ratio to Strand Data

IM-7 tow data (solid blue line) consistent with IM-7 COPV data (blue symbols)



Proof-of-concept Felicity ratio analysis of an IM-7 reinforced C/Ep COPV (blue dots) superimposed on Kevlar 49 (green line), T1000 (red line), and IM7 (blue line) single tow data

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Conclusion

- NDE has proven highly effective in real-time characterization of COPVs during testing
- NDE is reasonably effective in evaluating the health of COPVs, but still more work is needed to make it more quantitative